Search for Technicolor Particles Produced in Association with a W Boson at CDF

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We present a search for the technicolor particles ρ_T and π_T in the process $p\bar{p} \to \rho_T \to W\pi_T$ at a center of mass energy of $\sqrt{s} = 1.96\,\mathrm{TeV}$. The search uses a data sample corresponding to approximately $1.9\,\mathrm{fb}^{-1}$ of integrated luminosity accumulated by the CDF II detector at the Fermilab Tevatron. The event signature we consider is $W \to \ell\nu$ and $\pi_T \to b\bar{b}, b\bar{c}$ or $b\bar{u}$ depending on the π_T charge. We select events with a single high-p_T electron or muon, large missing transverse energy, and two jets. Jets corresponding to bottom quarks are identified with multiple b-tagging algorithms. The observed number of events and the invariant mass distributions are consistent with the standard model background expectations, and we exclude a region at 95% confidence level in the ρ_T-π_T mass plane. As a result, a large fraction of the region $m(\rho_T)$ = 180 - 250 GeV/c^2 and $m(\pi_T)$ = 95 - 145 GeV/c^2 is excluded.

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The mechanism of electroweak symmetry breaking in nature is still unknown. The standard model (SM) assumes the Higgs mechanism [1] but provides no explanation as to why there should be a fundamental scalar Higgs field with a non-zero vacuum expectation value. An alternative approach is to seek a dynamical mechanism for the symmetry breaking. The scenario known as technicolor [2–4] proposes a new strong interaction, modeled on QCD, which spontaneously breaks electroweak symmetry in an analogous way to the breaking of chiral symmetry in QCD. The strong technicolor interaction between the new technifermions results in a vacuum technifermion condensate which can break electroweak symmetry and hence give mass to the $W^{\pm}$ and Z gauge bosons. As in QCD, the technicolor interaction should give rise to technipions (π_T) and other technimesons. In this Letter we report the results of a search for technipions produced in association with a W boson from technirho (ρ_T) decay, $\rho_T \to W\pi_T$, in the context of the technicolor straw man (TCSM) model [5]. Like the SM Higgs boson, the technipion coupling to fermions is proportional to mass, and hence the technipion predominantly decays to $b\bar{b}$, $b\bar{c}$, or $b\bar{u}$, depending on its charge. The resulting final state is identified by selecting events with exactly one high-p_T electron or muon candidate, large missing transverse energy, and two jets, at least one of which is identified as containing a b-quark (b-tagged).

The data sample used here corresponds to $1.9\pm0.1\,\mathrm{fb}^{-1}$ of integrated luminosity, nearly five times the sample used in the previous Tevatron searches [6, 7]. The searches at LEP were able to exclude ρ_T production at 95% confidence level for $90 < m_{\rho_T} < 206.7\,\mathrm{GeV}/c^2$, independently of the assumed π_T mass and other model parameters [8].

The CDF II [9] is a general purpose detector to study $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\mathrm{TeV}$ at the Fermilab Tevatron. It consists of a cylindrical magnetic spectrometer, surrounded by electromagnetic and hadronic calorimeters. Charged particle tracking is performed with microstrip silicon detectors surrounded by a large cylindrical multilayer drift chamber, both immersed in a 1.4 T solenoidal magnetic field aligned coaxially with the incoming beams. Jets are identified as collections of electromagnetic and hadronic energy deposits in calorimeter towers, which are clustered using an iterative cone algorithm with a cone of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$ [10]. Muons are identified by a system of drift chambers and scintillators placed outside the calorimeter at a depth of at least five nuclear interaction lengths from the interaction region.

Events are collected using high-p_T electron or muon triggers with a three-level selection filter. The first two levels identify purely electromagnetic calorimeter clusters, or require that track segments in the muon chambers align with tracks in the drift chamber having $p_T > 8\,\mathrm{GeV}/c$. The third-level trigger requires an electron (muon) with $E_T > 18\,\mathrm{GeV}$ ($p_T > 18\,\mathrm{GeV}/c$).

Events are further required to have exactly one electron or muon candidate, large missing transverse energy ($\not\!\!E_T > 20\,\mathrm{GeV}$) [10], and two jets. The electron or muon must be within the central part of the detector, in the pseudorapidity regions $|\eta| < 1.1$ or $|\eta| < 1.0$, respectively, and must have $E_T > 20\,\mathrm{GeV}$ or $p_T > 20\,\mathrm{GeV}$. Because the lepton from a leptonic W decay is well isolated from the rest of the event, the energy deposits in calorimeter towers within the cone of $\Delta R = 0.4$ surrounding the lepton is required to contain less than 10% of the lepton energy. It must also be no more than 5 cm in z away from the primary event vertex, which is defined by fitting a subset of charged particle tracks in the event to a single vertex. To reduce the background from Z boson decays, we reject not only events with multiple high-p_T leptons, but also events in which the lepton and another high-p_T track of opposite sign form an invariant mass between $76 < M_{ll} < 106\,\mathrm{GeV}/c^2$. Jets used in the analysis must fall within the acceptance of the silicon detector ($|\eta| < 2.0$) for reliable b-tagging, and they must have transverse energy greater than 20 GeV.

The primary background to this technicolor search is SM $W + 2$ jets production. However this process is dominated by light-flavor jets, while the technipion decay process should contain at least one b quark. Identifying these b-quark jets therefore helps to significantly suppress the background. We use two b-tagging algorithms: a secondary vertex finding algorithm [11] (SECVTX) and a jet probability tagging algorithm [12] (JETPROB). To further improve the purity of the SECVTX sample, a neural network (NN) filter has been trained to reject tagged jets

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originating from charm or light-quarks [11]. The search sensitivity is maximized by using three exclusive b-tagged event categories. The first category (ST+ST) contains events with two SECVTX b-tagged jets. The second category (ST+JP) consists of events where only one of the jets is b-tagged by SECVTX and the second jet is only b-tagged by JETPROB. The third category (ST+NNtag) is for events which do not belong to the first two categories but contain exactly one SECVTX b-tagged jet that also passes the NN filter.

The selected event sample includes contributions from other standard model processes. The largest backgrounds are due to W + jets production, $t\bar{t}$ production, and non-W multijet production, with small contributions from single top, diboson (WW, WZ, ZZ), and $Z \to \tau\tau$ production. These backgrounds are estimated using the same methods as the standard model Higgs boson search analysis in the W + 2 jets channel [13]. A summary of the estimated backgrounds to the W + 2 jets final state is shown in Table I, along with the number of observed events in data and the expected technicolor signal events for a mass hypothesis of $m(\rho_T, \pi_T) = (180, 95), (200, 115), (250, 145)\,\mathrm{GeV}/c^2$, respectively.

The signal process in $\rho_T \to W\pi_T \to l\nu j_1 j_2$ is expected to show resonant peaks in both the dijet and W + 2 jets mass spectra. We reconstruct the p_z of the neutrino by constraining the invariant mass of the lepton-neutrino pair to the W boson mass, which gives a two-fold ambiguity. We select the solution with the smaller $|p_z|$, since that is more probable given the production mechanism of this heavy state; if there is no real solution, we set the imaginary part of solution to zero. Figure 1 shows the observed dijet mass spectra in the double tagged (ST+ST and ST+JP) and one SECVTX with NN filter tagged 2 jets samples, along with the distributions expected from the background processes. Figure 2 shows the Q-value distribution in each b-tagging category, the mass difference defined as $Q = m(\rho_T) - m(\pi_T) - m(W)$, which exploits the fact that the Q-value for the ρ_T decay is quite small and consequently the resolution of the mass difference is better than the mass of the ρ_T itself. The signal distributions from the charged and neutral technicolor particles with $m_{\rho_T} = 200\,\mathrm{GeV}/c^2$ and $m_{\pi_T} = 115\,\mathrm{GeV}/c^2$ are also shown for comparison. There is no significant excess observed in either the dijet mass or Q-value distributions.

The acceptance for $\rho_T \to W\pi_T \to \ell\nu b\bar{b}, b\bar{c}, b\bar{u}$ is calculated from samples generated with the PYTHIA Monte Carlo program [14] using ρ_T mass values between 180 and $250\,\mathrm{GeV}/c^2$ with a step of 10 GeV/c^2, and $max(m(\rho_T)/2, m(W)) < m(\pi_T) < m(\rho_T) - m(W)$ where the decay $\rho_T \to W\pi_T$ dominates.

The total acceptances for ST+ST, ST+JP and ST+NNtag events of $\pi_T^0 \to b\bar{b}$ ($\pi_T^\pm \to b\bar{c}, b\bar{u}$) are $0.32 - 0.45\%\,(0.04 - 0.06\%)$, $0.23 - 0.31\%\,(0.09 - 0.13\%)$, and $0.66 - 0.81\%\,(0.69 - 0.83\%)$, increasing linearly as function of $m(\rho_T, \pi_T)$ from (180,95) to (250,165) GeV/c^2. The dominant systematic uncertainty on the acceptance for the $\pi_T^0 \to b\bar{b}$ ($\pi_T^\pm \to b\bar{c}, b\bar{u}$) process originates from the uncertainty on the b-tagging efficiencies, which is a 8.4% (9.4%) relative error for ST+ST, a 9.2% (17.0%) relative error for ST+JP, and a 4.3% (4.3%) relative error for ST+NNtag. Additional sources of systematic error include the jet energy scale, the lepton identification efficiency, parton distribution functions, and the initial and final state radiation models [15]. The systematic uncertainties associated with the shape of dijet invariant mass and Q-value are also studied by varying the jet energy scale and the initial and final state radiation, which are found to have a negligible impact on the final results.

Since there is no significant excess of events in the data compared to the predicted background, we set the 95% C.L. excluded region on technicolor production as a function of the technicolor particle mass. A 2-dimensional binned maximum-likelihood technique which assumes Poisson statistics is used on the 2-dimensional distribution of dijet invariant mass vs Q-value by constraining the number of background events within the uncertainties. To calculate the 95% C.L. excluded region, we use neutral and charged π_T signals simultaneously. A Bayesian interval is constructed from the cumulative likelihood distributions and a prior probability density function uniform in the number of technicolor signal events. The 95% confidence level upper limit is defined to be the value s_{up} for which $\int_0^{s_{\mathrm{up}}} L(s)ds / \int_0^\infty L(s)ds = 0.95$. The number of signal events is then converted to a technicolor particle production cross section times branching fraction $\sigma(p\bar{p} \to W\pi_T^0(\pi_T^\pm)) \cdot BR(\pi_T^0(\pi_T^\pm) \to b\bar{b}(b\bar{c}, b\bar{u}))$.

The expected and observed 95% confidence level excluded region in the ρ_T-π_T mass plane is shown in Fig. 3. Almost the entire region we have looked at in this search is excluded at 95% confidence level, except the area near the $W\pi_T$ production threshold with $m(\rho_T) \geq 220\,\mathrm{GeV}/c^2$ and $m(\pi_T) \geq 125\,\mathrm{GeV}/c^2$.

In summary, we have performed a search for technicolor production $p\bar{p} \to \rho_T^{\pm/0} \to W^\pm\pi_T^{0/\mp} \to \ell\nu b\bar{b}$, $\ell\nu b\bar{c}$, or $\ell\nu b\bar{u}$ using $1.9\,\mathrm{fb}^{-1}$ of integrated luminosity accumulated by the CDF II detector. A large fraction of the region of $m(\rho_T)$ = 180 - $250\,\mathrm{GeV}/c^2$ and $m(\pi_T)$ = 95 - $145\,\mathrm{GeV}/c^2$ is excluded at 95% confidence level, based on the technicolor Straw Man model. This measurement excludes a much larger region than the previous Tevatron searches [6, 7].

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Selection	ST+ST	ST+JP	ST+NNtag
$Wb\bar{b}$	37.9±16.9	31.2±14.0	215.6±92.3
$Wc\bar{c}$	2.9±1.2	7.9±3.4	167.0±62.1
Mistag	3.9±0.4	11.7±0.9	107.1±9.4
$t\bar{t}$	19.0±2.9	15.6±2.4	60.7±9.3
Single top	8.5±1.2	7.0±1.0	44.0±6.4
non-W	5.5±1.0	9.6±1.7	184.7±33.0
WW	0.17±0.02	0.9±0.1	15.4±1.9
WZ	2.41±0.26	1.8±0.2	7.6±0.8
ZZ	0.06±0.01	0.08±0.01	0.31±0.03
$Z \to \tau\tau$	0.25±0.04	1.3±0.2	7.3±1.1
Total Bkg.	80.6±18.8	87.0±18.0	809.6±159.4
$m(\rho_T, \pi_T) = (180, 95)$	22.9±2.9	19.5±2.6	81.9 ± 5.6
$m(\rho_T, \pi_T) = (200, 115)$	12.7±1.6	10.5±1.4	43.7 ± 3.0
$m(\rho_T, \pi_T) = (250, 145)$	7.7±1.0	6.6±0.9	27.3 ± 1.9
Data Events	83	90	805

TABLE I: Predicted sample composition and observed number of $W + 2$ jets in each b-tagging category, along with the expected signal events for a mass hypothesis of $m(\rho_T, \pi_T) = (180, 95), (200, 115), (250, 145)$ GeV/c^2, respectively.

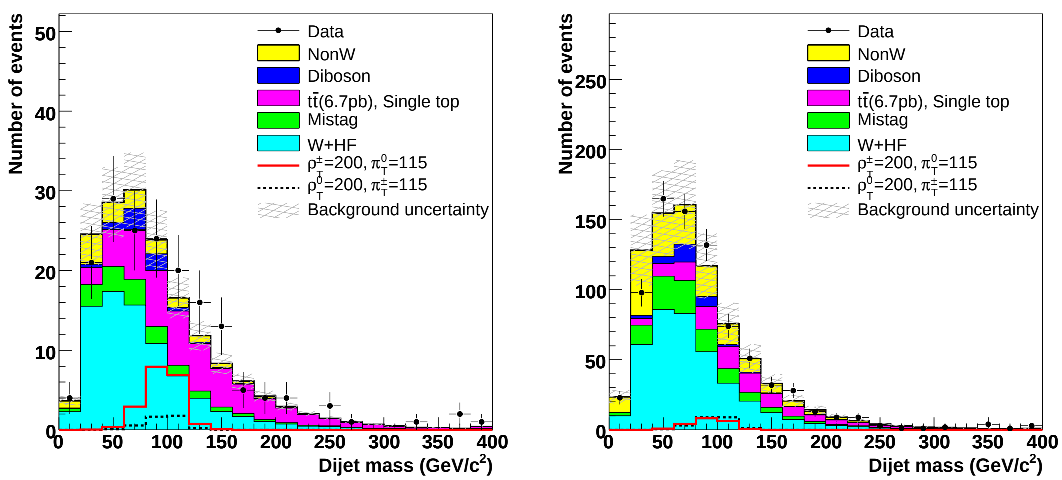

FIG. 1: Reconstructed dijet mass distributions for $W + 2$ jets events. The left is for double tags (ST+ST and ST+JP) and the right is for single tag (ST+NNtag) events.

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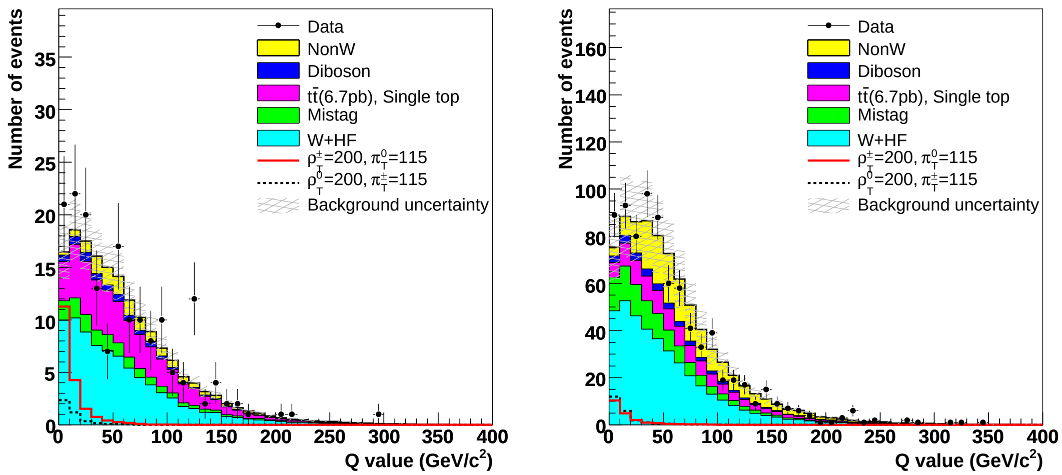

FIG. 2: Reconstructed Q-value distributions for W + 2 jets events, where $Q = m(\rho_T) - m(\pi_T) - m(W)$. The left is for double tags (ST+ST and ST+JP) and the right is for single tag (ST+NNtag) events.

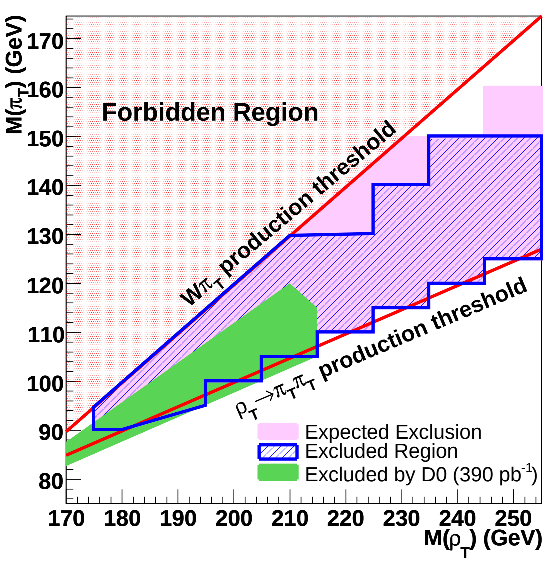

FIG. 3: 95% confidence level excluded region on technicolor particles production cross section times branching fraction as a function of $m(\rho_T)$ and $m(\pi_T)$ mass hypothesis. The expected excluded region from background-only pseudoexperiments are shown with the observed results from this analysis and D0 searches.

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